Original Article

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Differentiation of Early Osteoarthritis and Healthy Knee Joints Using Spectral Distribution of Vibroarthrographic Signals

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Objective: Osteoarthritis (OA), one of the most common knee joint diseases, is generally diagnosed through medical imaging. However, determining whether the knee joint is in the initial stage of OA can be difficult. Therefore, in this study, we distinguished grade-I OA knee joints from normal joints by using the spectra of knee vibroarthrographic (VAG) signals recorded during active swinging, passive swinging, and squatting.

Methods: Three types of VAG signals and angular changes in the knee joint were simultaneously recorded during active swinging, passive swinging, and squatting in 26 control subjects with healthy knees and 31 patients with grade-I OA knees.

Results: During passive swinging, the energy ratios of the VAG signals recorded at the lateral condyle and mid-patella of the grade-I OA group were significantly higher at 10 – 200 Hz but smaller at 400 – 1,000 and 1,000 – 2,500 Hz (all $p < 0.05$) compared with those of the age-matched control group. During squatting, the grade-I OA knees had significantly higher energy ratios at 10 – 200 Hz and lower energy ratios at 400 – 1,000 and 1,000 – 2,500 Hz for the VAG signals recorded at the lateral condyle, mid-patella, and medial condyle (all $p < 0.5$).

Conclusions: A part of the energy of the VAG signals in the grade-I OA knee joints shifted from high to low frequencies during passive and squatting movements. This may enable physicians to achieve the early differentiation of grade-I OA knees from normal knees.

Key words: knee joint, osteoarthritis, vibroarthrography, spectrum, energy ratio

Introduction

Osteoarthritis (OA) of the knee joint is a disabling disease resulting in joint discomfort, restricted motion, and diminished function. Arthritic degeneration of injured knees results from various traumatic causes. However, nontraumatic knee joint conditions could also lead to OA. Both traumatic and nontraumatic causes may lead to the femur, tibia, and patella developing irregular surfaces that may subsequently result in softening and fibrillating of the articular cartilage. All irregular surfaces cause painful inflammation of the knee joint when an individual is walking. Selecting treatment plans for knees with OA is often difficult because the natural history of

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OA progression is difficult to determine. Radiography is the most widely used method for diagnosing and monitoring OA progression in knees.[1] However, in the early stage of knee OA, X-rays may be unable to characterize the functional integrity of the cartilage. Although computed tomography and magnetic resonance imaging can assist in detecting knee OA, they cannot be routinely used for screening patients in clinical practice. Therefore, arthroscopy has become the gold standard for diagnosing cartilage conditions. However, arthroscopy cannot be practically used for repeated, long-term examinations.

Mechanical vibrations emitted from the knee joints during flexion or extension have been proposed to be associated with pathological conditions of the knee joint, and changes in the amplitude and frequency of the vibrations may be useful indicators of the roughness, softening, breakdown, or state of lubrication of articular cartilage surfaces.[2,3] Therefore, vibroarthrographic (VAG) signal analysis of these mechanical vibrations may be useful for detecting early knee OA and has the potential to become a noninvasive method for diagnosing knee-joint disorders.[3,4]

Because the sources of VAG signals are related to specific features of joints, such as crepitus or popping sounds, VAG signals may be useful for detecting whether a knee joint has OA or another disorder, and VAG arthrometry is an alternative technology for noninvasive detection of knee-joint pathologies.[5,6] Knee-joint VAG signals can be detected using accelerometers, electrostethoscope sensors, or other types of sensors attached to different areas around the knee joint.[7-9] The articular surfaces in the knees of healthy adults are generally smooth and slippery, with less cartilage friction or collision during leg motion. Therefore, the amplitude of the VAG signals for such knees is small. However, VAG signals produced by friction between degenerative articular cartilage demonstrate anomalous patterns on amplitude and frequency scales.[10] Accordingly, vibration arthrometry not only enables noninvasive and low-cost routine identification of knee disorders in clinical settings but also supports functional examination of the knee joint during leg movement.[2]

In most applications of vibration arthrometry, VAG signals are recorded on the surface of the knee joint during active or passive swinging under non-weight-bearing conditions.[4,11] In most daily activities, such as walking or running, the knee joints are under weight-bearing conditions and are required to support the full body weight. Therefore, active and passive swinging of the legs may not reflect the actual situation of the knee joints. Furthermore, VAG signals measured under actual weight-bearing conditions differ from those measured under non-weight-bearing conditions and may provide additional information related to joint abnormality. For example, Tanaka and Hoshiyama reported that VAG signals were stronger for 46 knees with OA at 50 – 99 and 100 – 149 Hz than for 49 age-matched control knees during standing-up and sitting-down movements.[12] Furthermore, Ołowiana et al. noted that the lowest VAG values occurred under unloaded conditions, and that increasing the applied load led to significant associated increases in the variation of mean square, mean range, and power spectral density values at the frequencies of 50 – 250 and 250 – 450 Hz.[13]

Therefore, the purpose of this study was to develop a multichannel measurement system that can be used to wirelessly detect vibration signals generated by knee-joint motion under weight-loaded and non-weight-loaded conditions that would enable patients to move freely without a wired connection.

Materials and Methods

Population

Fifty-seven participants were recruited

for this study: 26 normal healthy participants (control group) and 31 patients (OA group) with knee joints with grade-I OA. The normal participants were recruited from an outpatient clinic, had healthy medical histories, and had knees classified as normal (free from impairments related to the knee joint as determined through X-ray examination) through clinical examination. The Ahlbäck system was used to determine the radiographic OA classification grade in the patients in the OA group.[14] If a patient's knee had a joint space that had narrowed to less than 3 mm of the space or less than 50% of the other compartment, with or without subchondral sclerosis, the knee was categorized as having grade-I OA.

Protocol

This clinical trial was approved by the Institutional Review Board of E-Da Hospital of Kaohsiung, Taiwan (No. EMRP23101N), and informed consent was obtained from each participant prior to the start of the study. Each participant was asked to perform three movements: an active swing, a passive swing, and split squat-standing. For the active swing movement, each participant was asked to sit on a chair. The height of the chair was adjusted to ensure that the participant's lower legs could swing freely and that the tips of the participant's toes would not touch the ground. The participants were asked to actively swing one lower leg. Each active swing was completed over an approximate angle range of 90˚, between the femur and tibia (flexion), to 0˚ (full extension) and back to 90˚ within 2 seconds. Each participant completed six or seven movement cycles. Each participant warmed up prior to the experiment to ensure that they could maintain consistent knee flexion and extension speed. After participating in a training session in the sitting position, the participants completed active knee flexion and extension at a consistent velocity. The motion for the passive swinging was nearly the same as that for active swinging, with the exception of each participant's lower leg being passively flexed and extended by physicians. For the split squat-standing movement, each participant began in a standing position and completed a split squat movement, with the measured leg in front and its knee joint completing 90˚ knee flexion and with the other leg behind and its knee joint completing approximately 180˚ of full knee flexion. The participants then stood up. For the second split squat movement, the measured leg was behind, and the other leg was in front; the participant then stood up. The participants were asked to complete five to six cycles of 3-second split squat-standing movements. During squatting, the back leg was bearing a considerable portion of the participant's body weight.

Signal recording

An author-designed wireless measurement system was used to simultaneously record three VAG signals at the lateral condyle, mid-patella, and medial condyle of the knee joint, as presented in Figure 1. The system comprised three vibration sensing modules equipped with three accelerometers (352C22, PCB Piezotronics, NY, USA) to detect the VAG signals, an angle sensing module with a flexible sensor (FS-L-0095-103-ST, Spectra Symbol, UT, USA) that was used to identify the knee joint

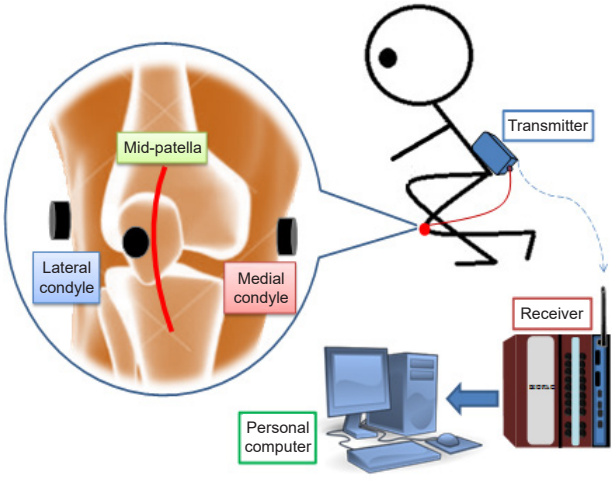

Fig. 1 Schematic of the wireless measurement system used to detect VAG and flexion angle signals.

angle, a wireless radio-frequency (RF) transmitter, a wireless RF receiver, a data acquisition device (MP150, BIOPAC Systems, CA, USA), and a personal computer. The Zigbee operational mode was employed. Therefore, the transmitter contained an analog to digital converter, a single-chip processor, and an RF generator. The receiver included an RF oscillator, a single-chip processor, and a digital to analog converter (BioNomadix, BIOPAC Systems). The analog VAG and angle signals were digitalized with a sampling frequency of 5 kHz and 12 bits/sample. The digitalized VAG and angle signals were stored for later analysis on the personal computer.

Frequency-domain analysis

Ten-second recordings of VAG signals from the three measuring positions were used to obtain power spectral densities through the fast Fourier transform algorithm (Matlab) after the mean for each position was subtracted. With reference to other investigations,[8,15] a high-pass filter with a cutoff frequency of 10 Hz was used to remove low-frequency interference from motion artifacts. Furthermore, with reference to other studies[12,13] and based on the authors' experience, the spectral power distribution of each VAG analog signal was divided into four frequency bands (FB1: 10 – 200 Hz, FB2: 200 – 400 Hz, FB3: 400 – 1,000 Hz, and FB4: 1,000 – 2,500 Hz). The total area under the spectral power distribution was normalized to unity. The energy ratio (ER; the integral of power between two frequencies) corresponding to individual frequency bands was defined as the band area divided by the total area under the spectral curve and was calculated using the following equation.

$$ER_n = \frac{\text{Band Area}_n}{\text{Total Area}} \times 100, \; n = 1, 2, 3, 4$$

Statistical analysis

Quantitative data (basic participant parameters and frequency band ERs) are expressed as mean ± standard deviation (SD). A two-tailed unpaired t-test was used to compare the differences in the ERs of various frequency bands of the VAG signals recorded at three locations during different movements. A p value of 0.05 or less was considered significant.

Results

Table 1 summarizes the basic information of the control (n = 26) and OA participants (n = 31). The sex ratios of the two groups differed. However, no differences were identified in age, height, weight, and body mass index between the groups. Typical VAG signal recordings for the lateral condyle, medial condyle, and middle patella of a control and an OA group member during active swinging, passive swinging, and split squat-standing are displayed in Figure 2. Identifying time-domain differences between the control and OA VAG signals acquired during active and passive swinging was difficult. However, direct visual inspection revealed that the amplitudes of the VAG signals obtained at the three locations of the typical control knee were higher than those of the typical OA knee.

Table 2 presents the ERs corresponding to different frequency bands of the VAG signals generated during active swinging in the control and OA groups. No difference was identified in the ERs of the four frequency bands of the two groups.

During passive swinging (Table 3), the OA group demonstrated a significant ER increase in FB1 at the both the lateral condyle (p = 0.006) and mid-patella (p = 0.029) compared

Table 1. Participants' basic information (mean ± SD).

	Control subjects (N = 26)	OA patients (N = 31)	p value
Age (year)	44.2 ± 19.3	51.6 ± 15.3	0.107
Male:Female	14:12	10:21	0.036
Height (cm)	165.8 ± 11.3	160.0 ± 8.0	0.061
Body weight (kg)	70.0 ± 15.9	66.1 ± 10.8	0.329
BMI	25.4 ± 4.9	25.8 ± 3.6	0.723

BMI: body mass index; OA: osteoarthritis.

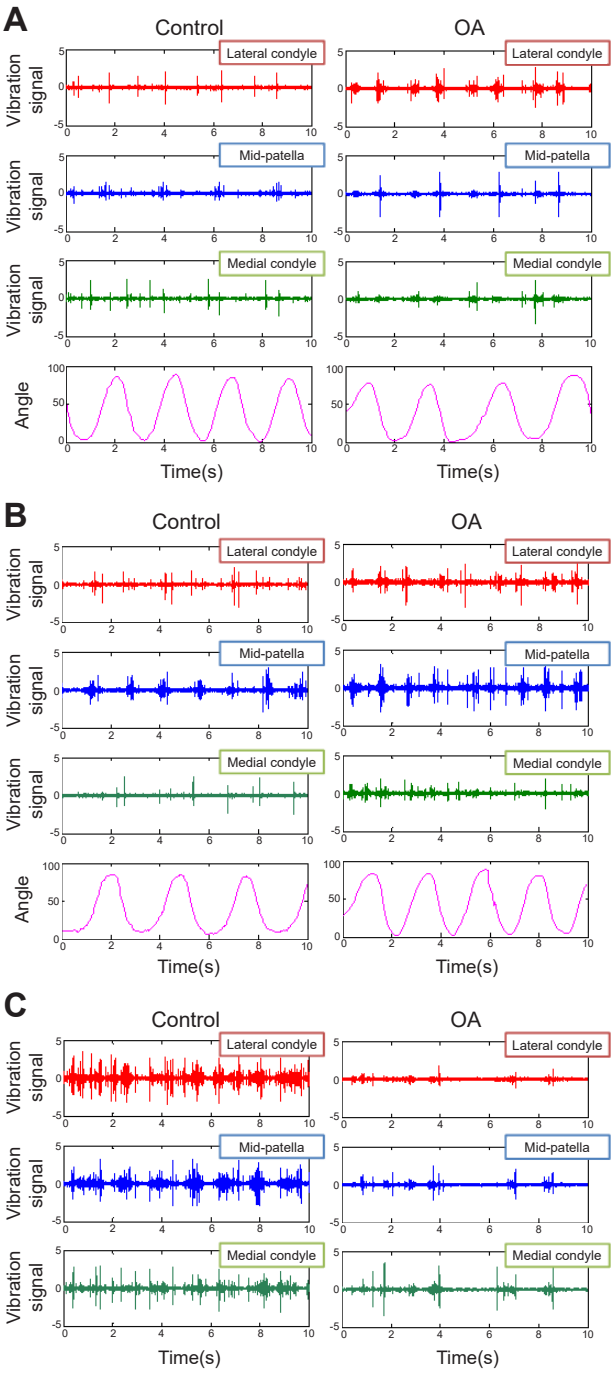

Fig. 2 (A) Active swinging; (B) Passive swinging; (C) Split squat-standing. Typical recordings of VAG signals simultaneously recorded at different positions in a control and OA knee joint during three movements.

with the control group. Significantly smaller ERs were identified in FB3 and FB4 in the OA group (FB3: $p = 0.007$ for the lateral condyle, $p = 0.044$ for the mid-patella; FB4: $p = 0.001$ for the lateral condyle, $p = 0.028$ for the mid-patella). However, no difference was identified in the ERs of the FB2 signals recorded at the three positions during passive movement. The two groups exhibited no differences in their ERs of the four frequency bands when the VAG signals at the medial condyle were generated by passive swinging.

Furthermore, during split squat-standing (Table 4), the ERs of the FB1 signals measured at the three positions were significantly higher in the OA group than in the control group ($p = 0.001$ for the lateral condyle; $p = 0.042$ for the medial condyle; $p = 0.007$ for the mid-patella). However, the OA group had significantly lower ERs for both FB3 and FB4 ($p < 0.001$ for the lateral condyle, medial condyle, and mid-patella). Notably, no difference was identified in the ERs of the FB2 signals recorded at the three locations of the two groups during split squat-standing.

Discussion

Compared with the control joints, the VAG signals recorded at the lateral condyle and mid-patella during passive movement in the OA joints had more high-frequency components and fewer low-frequency components under non-weight-bearing conditions, as indicated in Table 3. Furthermore, a similar phenomenon was identified during weight-bearing

Table 2. Comparison of the energy ratios of different VAG signal frequency bands generated during active swinging in the control and OA groups.

Position	Group	ER1 (%)	*p* value	ER2 (%)	*p* value	ER3 (%)	*p* value	ER4 (%)	*p* value
Lateral condyle	Control	35.13 ± 6.68		31.52 ± 3.75		28.05 ± 4.26		5.30 ± 0.67	
	OA	38.38 ± 7.82	0.100	29.97 ± 3.71	0.120	26.57 ± 4.48	0.205	5.09 ± 0.81	0.296
Mid-patella	Control	33.60 ± 9.35		32.87 ± 4.48		28.31 ± 6.01		5.22 ± 0.89	
	OA	37.62 ± 10.02	0.126	31.40 ± 4.53	0.228	26.07 ± 5.77	0.157	4.91 ± 0.93	0.205
Medial condyle	Control	40.65 ± 12.70		30.38 ± 6.38		24.24 ± 6.19		4.73 ± 0.89	
	OA	39.36 ± 8.72	0.649	30.73 ± 3.90	0.801	25.07 ± 5.38	0.587	4.48 ± 0.88	0.626

ER: energy ratio; OA: osteoarthritis; VAG: vibroarthrographic.

Table 3. Comparison of the energy ratios of different VAG signal frequency bands generated during passive swinging in the control and OA groups.

Position	Group	ER1 (%)	ER2 (%)	ER3 (%)	ER4(%)
Lateral condyle	Control	32.72 ± 6.57	31.67 ± 2.91	29.87 ± 4.33	5.74 ± 0.77
	OA	38.25 ± 7.96†	30.30 ± 3.73	26.40 ± 4.93†	5.04 ± 0.80†
Mid-patella	Control	32.17 ± 10.10	32.38 ± 4.32	29.96 ± 6.55	5.50 ± 0.98
	OA	38.23 ± 10.21*	30.31 ± 4.43	26.54 ± 5.96*	4.92 ± 0.96*
Medial condyle	Control	39.83 ± 15.57	29.91 ± 7.34	25.28 ± 7.99	4.99 ± 1.23
	OA	40.71 ± 9.16	28.66 ± 4.05	25.57 ± 5.69	5.06 ± 0.93

* $p < 0.05$; † $p < 0.01$. ER: energy ratio; OA: osteoarthritis; VAG: vibroarthrographic.

Table 4. Comparison of the energy ratios of different VAG signal frequency bands generated during split squat-standing in the control and OA groups.

Position	Group	ER1 (%)	ER2 (%)	ER3 (%)	ER4(%)
Lateral condyle	Control	35.93 ± 5.69	33.67 ± 3.53	25.72 ± 4.02	4.69 ± 1.19
	OA	50.78 ± 15.27$^{\#}$	35.40 ± 11.04	13.66 ± 5.79$^{\#}$	0.16 ± 0.06$^{\#}$
Mid-patella	Control	34.50 ± 10.42	32.83 ± 4.88	27.67 ± 6.07	5.00 ± 1.44
	OA	52.87 ± 22.05†	32.57 ± 13.92	14.36 ± 8.27$^{\#}$	0.20 ± 0.12$^{\#}$
Medial condyle	Control	39.82 ± 14.64	30.97 ± 6.53	24.67 ± 7.24	4.54 ± 1.46
	OA	52.50 ± 16.40*	34.29 ± 10.79	13.02 ± 7.78$^{\#}$	0.19 ± 0.12$^{\#}$

* $p < 0.05$; † $p < 0.01$; $^{\#}$ $p < 0.001$. ER: energy ratio; OA: osteoarthritis; VAG: vibroarthrographic.

split squat-standing (Table 4). Notably, some energy shifted from the high-frequency to the low-frequency band in the OA VAG signals, indicating energy normalization. Ołowiana et al. revealed that increasing the applied loads leads to a significant concomitant increase in power spectral density at the frequencies of 50 – 250 and 250 – 450 Hz.[13] The findings of the present study are partially consistent with these results. The differences in findings may have occurred because during movement, knee joints with a higher weight load may generate higher intensity vibroacoustic emissions resulting from higher contact stress and kinetic friction.

The energy shifting phenomenon was more notable when the control and OA groups performed complete split squat-standing. A study reported that OA knees produced a higher level of VAG signals at 50 – 99 and 100 – 149 Hz than age-matched control knees during standing-up and sitting-down.[12] This finding indicates that VAG signals generated by OA knees during motion may have a higher amplitude of vibration at frequencies less than 150 Hz. However, in the current results, VAG signals produced by OA knees during movement had higher and lower ERs at the 10 – 200 and 400 – 2,500 Hz frequency bands, respectively. Therefore, the results of the present study suggest that identifying changes through noninvasive VAG technology may be used for initial screening of patients with OA.

For passive swinging, the ERs of the VAG signals of the control and OA groups were significantly different for the lateral condyle and mid-patella, but not the medial condyle. For split squat-standing, the ERs of the VAG signals significantly differed for the lateral condyle, mid-patella, and medial condyle. The difference in the results for these two types of movement may be partially explained by the loading condition. No weight bearing is involved during passive swinging, whereas weight bearing is required during split squat-standing. Another reason may be that in passive swinging, the knee only performs 90° flexion, whereas in split squat-standing, complete 180° of full knee flexion is performed.

The knee is a lower extremity joint that supports nearly the entire weight of the body. Knee OA may be caused by the degeneration or loss of the articular cartilage. Detecting

knee-joint disorders in the early stage is essential because early detection can increase the therapeutic options available for delaying the degenerative process. Radiographs only provide positive results after such disorders have significantly progressed.[16] Although C-reactive proteins and erythrocyte sedimentation rates are indicators of inflammation, they are not site-specific. Furthermore, although arthroscopy can reveal damage to the cartilage that is not visible on radiographs, the technique is invasive. Magnetic resonance imaging is a noninvasive technique. However, its cost and availability prevent its routine used.

Most patients with arthritis are identified late in the disease stage, that is, after the disease has progressed beyond pharmacological or surgical interventions being able to delay or reverse the process. Being able to detect arthritis in its early stage may enable more effective intervention.

Biomarkers are indicators of normal biological processes, pathogenic processes, and pharmacological responses to a therapeutic intervention.[17] Bone markers indicate changes in serum levels and can be detected earlier than radiographical changes. However, few biomarkers have been identified for diagnosing OA in the early stage, and no biomarker is routinely used in clinical settings to monitor disease activity in patients with OA.

Imaging-based arthrographic modalities can provide anatomical images of joint cartilage surfaces but fail to reveal the functional integrity of the cartilage.[18] Knee-joint auscultation completed by recording VAG signals during knee bending movements can be used to develop a noninvasive diagnostic tool. Externally detected VAG signals could contain diagnostic information related to the roughness, softening, breakdown, or state of lubrication of the articular cartilage surfaces of the knee joints. Analysis of VAG signals can provide quantitative indices for the noninvasive diagnosis of articular cartilage breakdown and for OA staging. In addition, diagnosing knee-joint pathology through VAG signal analysis may reduce the required number of invasive diagnostic arthroscopic examinations. Our study findings offer insights into the characteristics of inpatients with OA knees and contribute to the understanding of the potential role of VAG signal analysis in OA staging.

The spectral distribution of VAG signals indicates that more than 99% of signal energy occurs between 0 and 2.5 kHz.[19] This may explain why the amount of energy corresponding to frequencies higher than 2.5 kHz was negligible in this study. We divided the VAG spectrum into four frequency bands (FB1 – FB4) based on the amplitudes of their ERs and compared the bands of the control and OA groups.

The activity of soft tissues, including muscles, tendons, and ligaments, around the knee joint directly affects the tibio-femoral joint load. High moments and forces, such as those generated by squatting, can result in high stress at high angles of knee flexion and can cause pathological changes in the knee joint.[20,21] The results of our study revealed significantly different VAG signals in the OA and control groups. Moreover, different results were obtained at different measuring sites. Generally, passive swinging and split squat-standing led to VAG variation at the lateral condyle and mid-patellar. However, joint pain usually originates from the medial side of the knee.[22] To prevent knee joint pain, individuals modify their gait patterns, which results in alterations in contact mechanics. The contact pressure of the knee joint is redistributed from the medial to lateral side. The articular cartilage of the medial tibia plateau is approximately three times thicker than that of the lateral plateau. The damping effect of the soft tissue may lead VAG signals to become less sensitive in the medial region. Therefore, further investigations, such as arthroscopic imaging, may be required verify the actual location and severity

of knee-joint degeneration.

Our results failed to verify that OA knees can be distinguished from normal knees by using the spectrum of VAG signals acquired at different knee positions during active swinging. During active swinging, several types of muscles, tendons, and other soft tissues around the knee actively and collectively contribute to the bending movement. Therefore, the noise created by the soft tissues may be superimposed on the VAG signals. During passive swinging and split squat-standing, the energy in the four frequency bands is redistributed in the OA VAG signals, which generally causes the energy to shift from high- to low-frequency bands. Other research has been conducted for detecting knee-joint degeneration in the early stage by using acoustic recordings of joint sounds.[23] However, the frequency analyses of the study were likely to have experienced direct interference from environmental noise, which likely resulted in less sensitive identification of the variation between each frequency band. Therefore, in this study, we employed VAG signals, which have similar patterns to acoustic recordings, as an alternative approach for detecting changes in the knee-joint cartilage. This enabled the increase in the ER low-frequency bands in patients with OA to be connected to the joint sounds that are often identified in clinical practice. However, the limitations of human hearing would reduce the value of identifying variations in high-frequency bands in the early stage of OA. Our study has some limitations. The differences identifiable through VAG signals and radiography are insufficient and, therefore, cannot be used to determine real cartilage conditions. Real cartilage conditions require arthroscopy confirmation. We will likely address this limitation in our future research.

Conclusion

Knee joints with grade-I OA had a significantly higher amplitude of frequency components in the low-frequency band (10 – 100 Hz) but a lower amplitude of frequency components in the high-frequency band (400 – 2,500 Hz) of VAG signals than control knee joints did. This finding indicates that for grade-I OA knee joints, some of the energy of VAG signals is removed, from high to low frequencies, during passive and squatting movements. This observation suggests that knees with initial OA can be differentiated form normal knees by using the VAG signals from the lateral condyle and mid-patella during passive movement or from the lateral condyle, mid-patella, and medial condyle during split squat-standing.

Author Contributions

Technique Support, Jia-Jung Wang and Ting-Sheng Lin; Study Design, Jia-Jung Wang; Data Collection, Chun-Chien Chen; Patient Arrangement, Cheng-Yo Yen.

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Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the E-Da Hospital, Kaohsiung, Taiwan (no. EMRP23101N).

Informed Consent Statement

Informed consent was obtained from each participant prior to initiation of the study.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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